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PLATE WAVE RESONANCE WITH AIR-COUPLED ULTRASONICS

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ABSTRACT. Air-coupled ultrasonic transducers can excite plate waves in metals and composites. The coincidence effect, i.e., the wave vector of plate wave coincides with projection of exciting airborne sound vector, leads to a resonance which strongly amplifies the sound transmission through the plate. The resonance depends on the angle of incidence and the frequency. In the present study, the incidence angle for maximum transmission (θ_{max}) is measured in plates of steel, aluminum, carbon fiber reinforced composites and honeycomb sandwich panels. The variations of (θ_{max}) with plate thickness are compared with theoretical values in steel, aluminum and quasi-isotropic carbon fiber composites. The enhanced transmission of air-coupled ultrasound at oblique incidence can substantially improve the probability of flaw detection in plates and especially in honeycomb structures. Experimental air-coupled ultrasonic scan of subtle flaws in CFRP laminates showed definite improvement of signal-to-noise ratio with oblique incidence at $\boldsymbol{\theta_{max}}$.

Keywords: Air-coupled Ultrasonics, Lamb Wave, Resonance
PACS: 81.70.-g

INTRODUCTION

Through-transmission is the most common and well known technique for ultrasonic non-destructive testing. Ultrasonic wave propagates through a defective zone of the object under test and interaction of the wave with defect causes changes of amplitude of the received signal. This technique is very useful when the energy of sound beam is low, such as in air-coupled ultrasonic.

An air-coupled ultrasonic measurement technique is very attractive for nondestructive testing of various materials and structures. The non-contact nature of the technique eliminates all contact anomalies. This technique has its greatest applicability for testing and characterizing damage materials such as carbon/glass fiber reinforced plastics, honeycomb.

In the air-coupled normal-incidence the signal strength at the receiver is very low due to the impedance mismatch between the air and the plate. In this work, we have improved the signal strength by changing the angle of incidence which in turn results in the generation of the Lamb waves in the plate like samples. Theoretically, infinite number of lamb wave modes exists, but the most useful measurement with air-coupled ultrasonic technique can be carried out with lower order symmetric S_0 and anti-symmetric A_0 modes. S_0 modes have high wave velocity and hence its ringing is not very easy to separate from the incident wave, while the A_0 waves are very slow and thus the signal can be very easily separated and identified.

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Lukkala et al. [1] stated that the acoustic partition may transmit sound through them in such a way that the pressure variation in the sound firstly excites a plate wave in the partition, and the flexural plate wave then re-radiates the sound to the next room. This phenomenon called 'coincidence effect' [2]. We can assume that in a honeycomb a similar wave mechanics is being followed. The front wave sitting on a honeycomb is excited in the lamb wave mode, this wave then generates waves in both the honeycomb and the intermediate air and the pressure waves are transmitted to the second face sheet of the honeycomb. This wave then is leaked into the air and is captured by the receiver.

In the present study, the resonance effect due to oblique incidence of air-coupled sound on steel, aluminum, carbon fiber reinforced composites and honeycomb sandwich are investigated. The signal with the largest amplitude is captured and it has been observed that this signal is larger than the normal incidence signal. This is the A_0 mode signal. Hence the signal/noise ratio is significantly improved which could lead to enhanced probability of flaw detection.

THEORY

The coincidence phenomenon could be useful in nondestructive testing when scale down to smaller wavelength and plate thickness. This phenomenon is described as the occurrence of resonance due to coincidence of wave vector of plate wave with projection of the existing airborne sound wave vector [1]. This phenomenon in optics is known as the Snell's law.

Let, airborne sound beam propagates with velocity $\mathbf{v}_0$ and the wave vector $\mathbf{k}_0$ impinge upon elastic thin plate. The beam impinges at an angle $\boldsymbol{\theta}$ with plate normal. The angle of refraction or transmittance is 90^0.

When, $\boldsymbol{\theta} = \boldsymbol{\theta}_k$ such that the projection of $\mathbf{k}_0$ matches with $\mathbf{k}_b$ as shown in Fig 1.

$$\text{Then, } \mathbf{k}_0 \operatorname{Sin} \boldsymbol{\theta}_k = \mathbf{k}_b \quad \text{or} \quad \mathbf{v}_0 = \mathbf{v}_b \operatorname{Sin} \boldsymbol{\theta}_k \tag{1}$$

Where, $\mathbf{v}_b$, phase velocity (plate wave) and $\mathbf{k}_b$, its wave vector

Under these conditions, resonance occurs, and the plate wave is excited.

The resonance takes place at $\mathbf{v}_b > \mathbf{v}_0$. It should be noted here that in general $\mathbf{v}_0$ is constant while $\mathbf{v}_b$ is dispersive and frequency dependent. Current study deals with the effect of oblique incidence angle for resonance in metals and composites of different thickness. When the plate resonates (or generates a Lamb wave) it transfers the energy into the surrounding medium and this has been called as the leaky Lamb wave. At resonance the

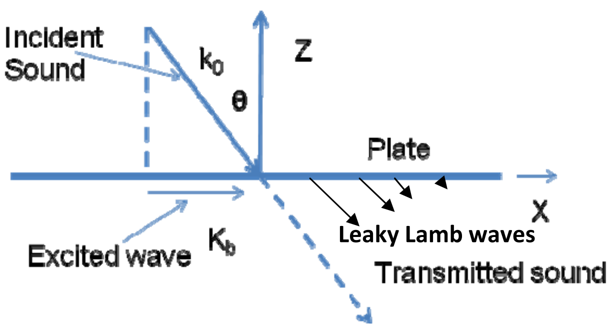

FIGURE 1. Generation of Lamb wave in a plate.

leaky lamb wave carries higher energy as compared to the wave in normal incidence. This is particularly true for the air-coupled transducers.

EXPERIMENTS

In this work air-coupled unfocussed planner transducers were used. The block diagram for this experiment is shown in Fig 2. The gas matrix piezoelectric (GMP^{TM}) transducers [3] used here have a central frequency of 100 kHz. The transmitter (38x38 mm) was excited by pulsar/receiver (Panametric NDT, 5077) at 300V and 100 kHz rectangular burst. The receiver (Φ38 mm) was connected to 40dB preamplifier (Panametric NDT). The test samples were placed 50mm away from transmitter. The experiments were carried out in through transmission mode and amplified signal were displayed on oscilloscope for measurement. The test specimens were subjected to pitching between $\pm 30^0$. All samples are shielded with foam partitions to avoid/minimize the leakage around the samples.

Test Specimen

These tests were conducted on plates of steel, aluminum and fiber reinforced composites. The thicknesses of the plates are over a very wide range as will be seen in the results section. Further tests were performed on aluminum face sheet aluminum core samples. In these samples the core thickness was kept fixed and face-sheet thickness was different between the samples.

RESULTS & DISCUSSION

The transmitter and receiver are aligned as shown in Fig 2 and the signal amplitude is measured. Now the plate is rotated and the amplitude of the A_0 mode is recorded. A series of typical time domain signal is as shown in Fig 3. The mode of the signal is identified by its time shift with thickness of plate of known transmission sound velocity. In addition to A_0 mode signal, there are several strong delayed signals observed. These signals move with plate position with respect to the transducers. Fig 3 (a to c) shows the received signal for an aluminum plate of thickness 4.8 mm kept at 1", 2", and 3" away from transmitter respectively. The A_0 mode signal (encircled) does not shift in time with plate position. Thus, other signals are identified as the multiple reflections in air/solid interfaces.

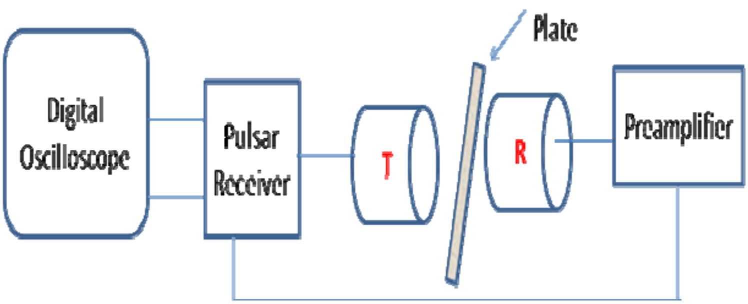

FIGURE 2. Experimental Set up.

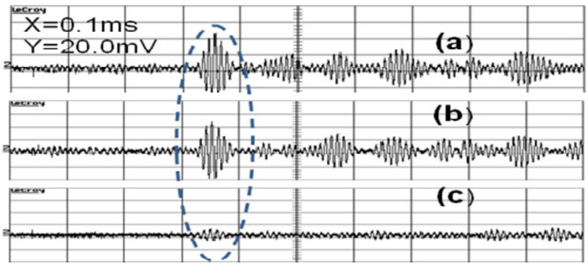

FIGURE 3. Multiple reflections in Al plate at a) 1 inch apart from Transmitter, b) 2 inch, and c) 3 inch.

The time domain signals amplitudes are recorded at different oblique angles. The angles at maximum amplitude in +ve and –ve are averaged and denoted as $\boldsymbol{\theta_{max}}$. Demcenko et al. [4] suggested, the theoretical values of angles θ can be calculated from the dispersion curve for corresponding material.

$$\boldsymbol{\theta = \mathrm{Sin}^{-1}\,(v_{air}/v_{lamb})}, \tag{2}$$

Where, $\mathbf{v_{lamb}}$ is the phase velocity described in dispersion curve, and $\mathbf{v_{air}}$ = 330m/s.

Steel

Fig 4a shows the typical time-domain signal for a steel plate of thickness 0.81 mm normal incidence while Fig 4b shows the same plate at an angle of incidence of 30^o. It is seen that the maximum amplitude for A_0 (encircled) mode signal at oblique angle is five times higher than the amplitude for normal incidence. The angle of incidence is recorded for various angles for each plate and a typical plot is as shown in Fig 5. $\boldsymbol{\theta_{max}}$, which is the average of the maximum angle for positive and negative angles, is next plotted as the plate thicknesses are changed as shown in Fig 6. The theoretical representation of the same material, [5] is also plotted for comparison. Theoretical and experimental values are fairly close. The difference between the two curves can be explained by the fact that the density of the two plates could be different.

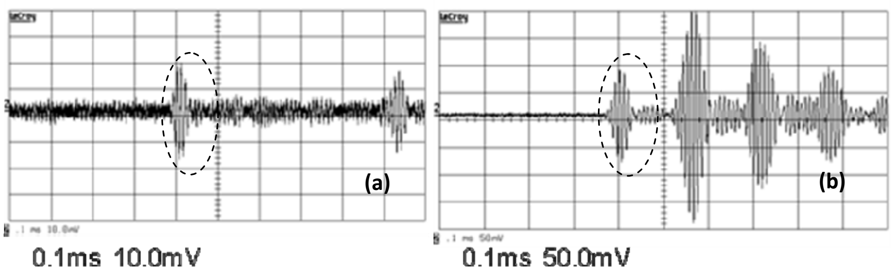

FIGURE 4. (a) Steel plate of thickness 0.81mm at incidence angles 0^0 and (b) 30^0**.**

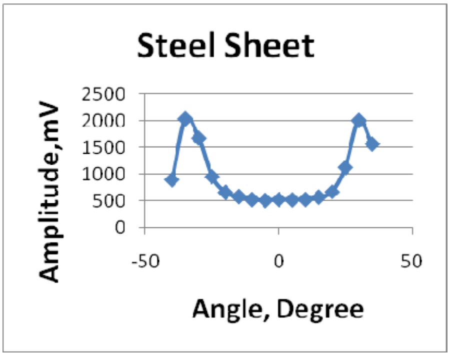

FIGURE 5. Signal amplitude variation with the angle of incidence for a steel plate of thickness 0.457mm.

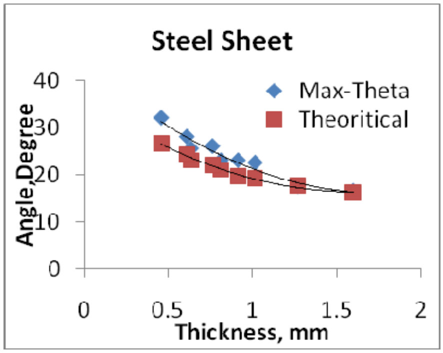

FIGURE 6. Experimental and theoretical θ_{max} for Steel Plates of different thicknesses.

Aluminum

Aluminum plates of various dimensions were examined next. Due lack of penetration power of sound beam, the experiment was limited to plate thickness of up to 6.4mm In case of aluminum, the maximum amplitude for A_0 (encircled) mode signal at oblique angle is 2-3 times higher than normal incidence, as shown in Fig. 7. The calculated $\boldsymbol{\theta_{max}}$ from experiment and theoretical [6] valued for aluminum are compared in Fig 8.

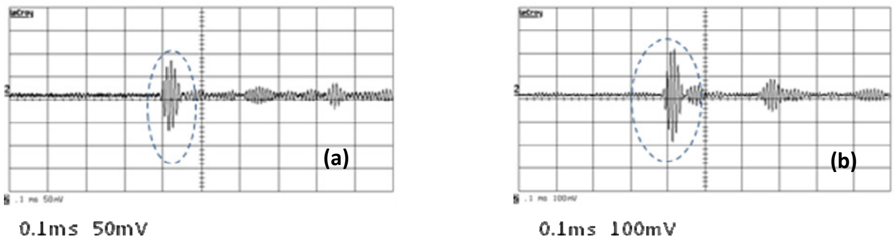

FIGURE 7. (a) Aluminum plate of thickness 1.2mm at incidence angles 0^0 and (b) 20^0.

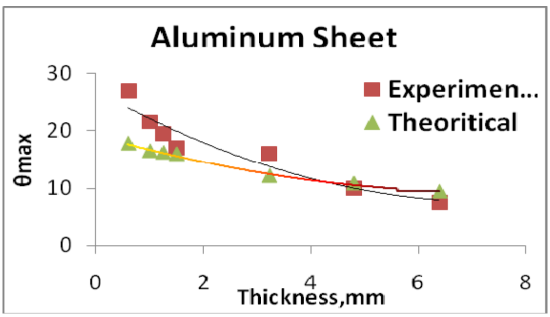

FIGURE 8. Experimental and theoretical θ_{max} for Aluminum plates of different thicknesses.

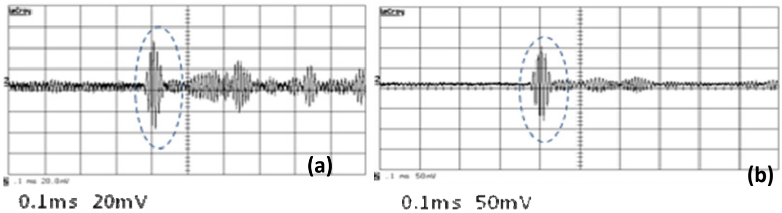

FIGURE 9. (a) CFRP plate of thickness 4.0mm at incidence angles 0^0 and (b) 10^0.

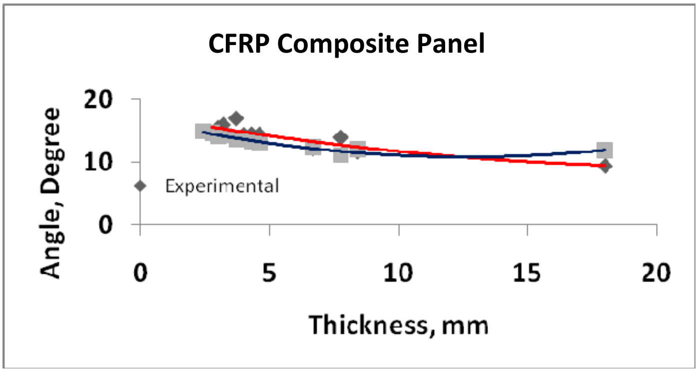

FIGURE 10. Experimental and theoretical θ_{max} for CFRP plates of different thicknesses.

Carbon Fiber Reinforced Plastics Composites (CFRP)

In CFRP panels the transmitted signal amplitudes with oblique incidence are amplified in order of 2-3 times more than normal incidence, as shown in Fig. 9. The trend of $\boldsymbol{\theta}_{\mathbf{max}}$ variation with panel thickness in experimental results correlates very well with theoretical values described by Pierce et al. [7], as shown in Fig. 10.

Honeycomb Panel

The wave propagation in honeycomb structure is very complex. In fact, the detail analysis of the phenomenon of lamb wave interaction with honeycomb could not be found in literature. Kayzs et al [8] have numerically predicted the lamb wave interaction with honeycomb.

The investigated samples consist of aluminum skin of different thickness and a core between them. The honeycomb core is 25 mm thick with cell size of 2.7 mm and a wall thickness of 0.4 mm. The skin plates are bonded with AF163-2L adhesive which is cured at 275^0 F for 2 hours. The sound beam impinges on the panel in the glue direction of hexagonal cells. For the aluminum core honey comb sandwich, with aluminum face sheets, the transmitted signal due to oblique angle of incidence is also amplified in order of 2, as shown in Fig 11. It was observed that there is no significant alternation in $\boldsymbol{\theta}_{\mathbf{max}}$ due to change in face sheet skin thickness.

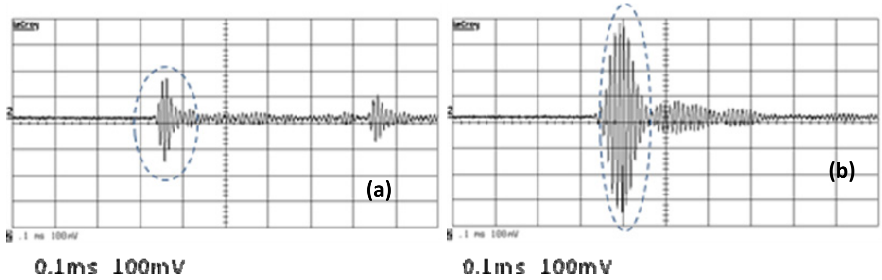

FIGURE 11. (a) Al-Al Honeycomb of skin thickness 0.55mm at incidence angles 0^0 and (b) 15^0.

As has been observed in all the above cases, the signal amplitude due to Lamb waves always amplified the observed signal. It can be conjectured that a stronger signal with a better signal/noise ratio would improve the damage detection resolution.

To prove this hypothesis, experiments were carried out on woven graphite-epoxy laminate of 48 plies which contain very weak flaws [9]. These panels have two different types of flaws namely, resin rich and polyethylene film insert of 1.5” diameter. The laminates are 4 mm thick and the foreign object, polyethylene film of few mils thick and resin rich area are at two plies down from top surface.

These panels were scanned with QMI air-coupled transducer in normal and 15^0 angular position. The C-scan image in through transmission mode shows a significant improvement in flaw detection in composites with oblique angle scanning, as can be seen in Fig. 12. Fig 12 (a) shows a sample with a very week flaw, a resin rich circular zone and the Fig 12(b) the same plate interrogated by the air-coupled technique at an incidence angle of 15^0. No signal processing was performed to enhance the signals. Similar experiments are carried out on polyethylene inserted laminate and the oblique incidence scan enhanced the flaw detection as shown in Fig 13. Signal processing was performed to enhance the flaw detectability.

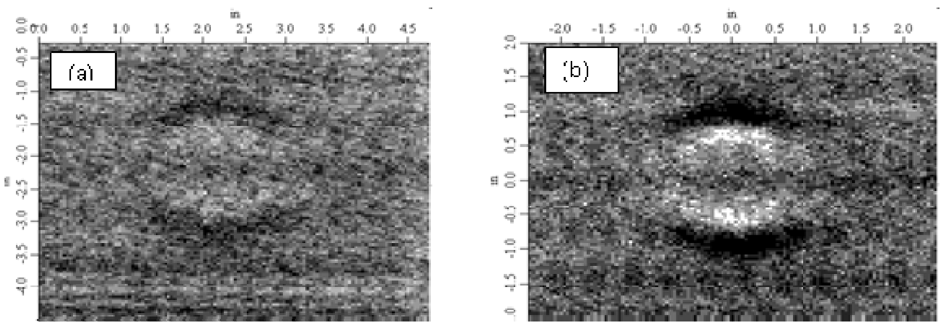

FIGURE 12. CFRP Plate with a local resin rich area at two plies down, at incidence angles, (a) 0^0 and (b) 15^0.

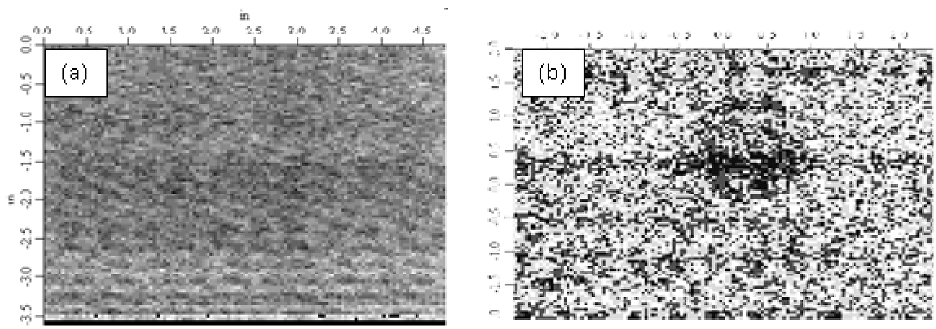

FIGURE 13. Plate with polyethylene 2 plies down, at incidence angles, (a) 0^0 and (b) 15^0.

CONCLUSION

Lamb wave A_0 mode interaction with metal, composites and honeycomb sandwich are investigated with air-coupled ultrasonic technique. The resonance which results in Lamb waves travelling in the plane of the plate strongly amplify the signal which is recorded at the receiver. Even for the lossy material such as carbon fiber reinforced composites and aluminum honeycomb sandwich the signal amplification is two times. This amplified signal has been used for the flaw detection. Experimental air-coupled ultrasonic scan of subtle flaws in CFRP laminates showed significant improvement of signal to noise ratio with oblique incidence at $\boldsymbol{\theta}_{\mathbf{max}}$ which resulted in a better damage detection in these samples.

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